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Gamma-ray bursts from quark stars

B. Paczyński[1]★ and P. Haensel[1]★

[1]*Princeton University Observatory, Peyton Hall, Princeton, NJ 08544, USA*

[2]*N. Copernicus Astronomical Centre, Polish Academy of Sciences, Bartycka 18, PL-00-716 Warszawa, Poland*

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ABSTRACT

Long gamma-ray bursts (GRBs) are believed to be related to the explosion of Type Ic supernovae, which have been stripped of their hydrogen and helium envelopes. There appear to be two types of these explosions: those that are approximately spherical (GRB 980425/SN 1998bw), and which are associated with weak bursts; and the classical GRBs which generate ultrarelativistic jets (GRB 030329/SN 2003dh). If this bimodality is real, *Swift* will provide clear evidence for it.

We propose that classical powerful GRBs, which generate ultrarelativistic outflows, are a result of the formation of quark stars. Quark stars may provide additional energy for the explosion of Type Ic supernovae, but far more important is the creation of a surface which acts as a membrane that cannot be penetrated by baryons. A surface of a quark star allows only ultrarelativistic matter to escape: photons, neutrinos, electron–positron pairs and magnetic fields. The formation of a quark star follows several minutes after the initial core collapse. Possible evidence for this time delay is provided by BATSE precursors to GRBs, as analysed by Lazzati.

Key words: dense matter – stars: neutron – supernovae: general – gamma-rays: bursts.

1 INTRODUCTION

It is generally accepted that long gamma-ray bursts (GRBs) are associated with star-forming regions (Paczyński 1998). More specifically, they are related to supernovae (SNe) of Type Ic, the core collapse events of massive stars stripped of their hydrogen and helium envelopes (Filippenko 1997; Iwamoto et al. 1998; Heger et al. 2003; Stanek 2004; Stanek et al. 2005, and references therein). While the SN/GRB connection was gradually emerging, it was most clearly demonstrated by the recent GRB 030329, associated with SN 2003dh (Stanek et al. 2003; Vanderspek et al. 2004).

We propose that there are two types of SNe Ic associated with GRBs. One is a more or less spherical explosion as originally described by Colgate (1968), prior to the discovery of the first GRBs (Klebesadel, Strong & Olson 1973). The spherical model was refined (Chevalier & Li 1999; Tan, Matzner & McKee 2001), and it may be relevant to events like SN 1998bw/GRB 980425 (Galama et al. 1998; Iwamoto et al. 1998) and SN 2001em (Stockdale et al. 2004, 2005; Bietenholtz & Bartel 2005). The other kind, with a strong ultrarelativistic jet, is a classical long GRB, much more powerful in gamma-rays than the first type. The proposed bimodality, if real, will be verified with *Swift*.

We speculate about the physical reason for the difference between the two types of SNe. We propose that the strong ultrarelativistic outflows develop when the collapsing core becomes a quark star. These hypothetical stars are built of self-bound quark matter (Witten 1984; Haensel, Zdunik & Schaeffer 1986; Alcock, Farhi & Olinto 1986). The total energy released could range from 10^{52} erg (Cheng & Dai 1996) to 10^{53} erg (Bombaci & Datta 2000), but we do not think that neutron star–strange star conversion is energetically decisive for SNe Ic. However, the formation of a baryon–quark membrane at a the surface of the collapsed compact object is most essential. The membrane can be penetrated by photons, electrons, positrons, neutrinos and the magnetic fields, i.e. by various forms of ultrarelativistic flow. The idea of a baryon–quark membrane is crucial for the model proposed in this Letter. Such a membrane prevents baryon contamination of the energy outflow from a hot quark star, a property already used in a model of short GRBs by Haensel, Paczyński & Amsterdamski (1991). Modelling of classical strong GRBs by energy outflow from a newly born quark star was previously suggested by several authors (Dai & Lu 1998; Wang et al. 2000; Ouyed & Sannino 2002; Berezhiani et al. 2003; Drago et al. 2004).

We shall outline the evolution to an SN Ic in the next section, and we shall discuss the theoretical possibility of the formation of a quark star in Section 3. We shall conclude this Letter with a discussion emphasizing the decisive role that *Swift* (Gehrels et al. 2004) will play in verifying our speculations.

2 EVOLUTION TO A SUPERNOVA

The evolution leading to the formation of an SN Ic is agreed upon (cf. Lee, Wijers & Brown 2000; Della Valle 2005, and references

★E-mail: bp@astro.princeton.edu (BP); haensel@camk.edu.pl (PH)

therein). We need a massive star to be stripped of hydrogen and helium envelopes. This may happen to a single Wolf–Rayet (WR) star, or to a WR star in a close binary system. In the latter case the binary may be compact and tidally locked, with rapid rotation as a consequence. When the star runs out of nuclear fuel the inner core collapses, ejecting a fair amount of Ni^{56}, which is the dominant energy source for SNe Ic (Iwamoto et al. 1998; Deng et al. 2005), with up to $10^{52.5}$ erg of kinetic energy. The relativistic outflow from a GRB is estimated to be $10^{51.5}$ erg (Frail, Waxman & Kulkarni 2000; Berger, Kulkarni & Frail 2004). Therefore the energetics of a GRB are only a relatively modest fraction of the SN Ic explosion energy. What makes it extraordinary is the bulk Lorentz factor of the ultra-relativistic component, estimated to be $\Gamma \sim 100$–1000 (Meszaros, Rees & Wijers 1998).

As far as we can tell, the evolution as described in the last paragraph is not controversial. What is controversial is the nature of the collapsed object: is it a neutron star or a black hole, and, even more controversially, what are the physical processes capable of ejecting bulk matter at $\Gamma \sim 300$? The common suggestions are neutrino–antineutrino annihilation (Woosley 1993), and magnetic fields (Usov 1992; Kluźniak & Ruderman 1998; Lee et al. 2000; Blandford 2002; Lyutikov & Blandford 2004, and references therein). The details are very complicated, and it is not possible to prove or disprove those models. The large bulk Lorentz factor is obtained by postulating suitable initial conditions, i.e. by replacing one puzzle with another.

Note that black holes are not a necessary condition for the formation of jets. Models of magnetized neutron stars by LeBlanc & Wilson (1970) demonstrated that they can form jets; even more importantly, it has been found observationally that the Crab and other compact stars do form jets (Mori et al. 2004, and references therein). Also note that neutron stars are formed out of stars with initial mass as high as 50 $M_\odot$ (Kaper et al. 1995; Clark et al. 2002; Figer et al. 2005; Gaensler et al. 2005).

If a quark star is formed, its surface separates the outside, where baryons can exist, from the inside where baryons are dissolved into quarks. The surface of a quark star separates baryonic matter from non-baryonic; it creates a membrane which may may be crossed only by electrons and positrons, photons, neutrino pairs and magnetic fields, automatically generating the conditions needed for an ultrarelativistic outflow of a classical GRB. There is a price to be paid: we do not know if quark stars exist.

At this stage a theory is too complicated or too uncertain, but we may ask: how far can we proceed using semi-empirical evidence?

Classical, powerful GRBs are believed to be jet-like, and if we are not in their beam we will not see a burst. Perhaps the anomalously weak GRB 980425 was due to a jet that missed us. However, no evidence for a jet several years after the explosion makes this scenario unlikely (Waxman 2004), and there is an emerging consensus that this was not a classical GRB (Soderberg, Frail & Wieringa 2004).

Following the suggestion by Paczyński (2001) and Granot & Loeb (2003), radio observations were carried out with the Very Large Array (VLA) (Stockdale et al. 2004; Bietenholtz & Bartel 2005) and the Very Long Baseline Array (VLBA) (Stockdale et al. 2005) to monitor an SN of Type Ic, SN 2001em. While strong radio emission was clearly detected, there was no evidence of a relativistic jet. It appears to be the second case of an SN Ic explosion that is not associated with a misaligned relativistic GRB jet.

Some SNe Ic are clearly associated with relativistic GRB jets, like GRB 030329/SN 2003dh (Stanek et al. 2003; Vanderspek et al. 2004), for which a superluminal jet moving at (3–5)c was observed by Taylor et al. (2004). Another good case of a GRB/SN association was provided by GRB 031203/SN 2003lw (Malesani et al. 2004). In addition, several GRB afterglows have very pronounced 'bumps' in their light curves, providing photometric evidence of the underlying SNe (Stanek et al. 2005; Zeh et al. 2005).

While this is only a preliminary conclusion, it appears that the powerful SNe Ic come in two types: those that generate classical GRBs with ultrarelativistic jets, and those that do not generate ultrarelativistic GRB jets. Note that the GRB events without relativistic jets are natural (Colgate 1968). The principle is very simple: a spherical explosion generates a shock wave which accelerates outer stellar shells to subrelativistic velocity and generates a weak GRB. What is extraordinary is the formation of powerful ultrarelativistic jets in some of these SNe Ic. What is the reason for this diversity, while the corresponding SNe appear to be similar? We suggest that the difference is due to formation of a core made of self-bound quark matter (SQM) in some of these explosive events. We should keep in mind, however, the possibility that the bimodality of SNe Ic is due to the presence or absence of rotation.

Our suggestion of a bimodal distribution of SN Ic properties is based on small-number statistics: two and two events of each type. This may be improved with *Swift*. According to Norris (2002, fig. 5) there is a population of about 90 BATSE bursts that are relatively nearby, with a typical distance of ~100 Mpc, which show a concentration towards the supergalactic plane. They seem to be related to GRB 980425. If some of these GRBs were jet-like, but we were not in the beam, we should be able to detect their radio emission several years later (Paczyński 2001; Granot & Loeb 2003). The proposed emission from a decelerated jet was not detected in SN 1998bw (Soderberg et al. 2004) or in SN 2001em (Stockdale et al. 2004, 2005; Bietenholtz & Bartel 2005), but with a much larger number of BATSE GRBs the radio emission should be detectable in at least some cases. The large BATSE error circles will not be a problem according to van Gorkom (private communication) and Frail (private communication), as the radio sky shows relatively little variability, and the late GRBs should stand out above the background.

Note that long-lag GRBs contribute only ~5 per cent at the bright end of BATSE luminosity function, but they dominate with 50 per cent at the faint end (cf. Norris 2002, figs 3 and 4). Their number counts are 'Euclidean', i.e. they are definitely nearby, at least by cosmological standards. *Swift* (Gehrels et al. 2004) will provide GRB coordinates accurate to an arcminute and even an arcsecond within a minute of the event. If the distribution discovered by Norris (2002) holds then *Swift* will provide a GRB/SN relation for many events and it will strengthen (or weaken) our proposal that some SN Ic explosions are more or less spherical (Colgate 1968), and some generate ultrarelativistic jets (the classical GRBs).

3 FORMATION OF A QUARK STAR

As we have already mentioned in Section 1, the total energy 10^{52}–10^{53} erg released in the neutron star–quark star conversion is not very important for the energetics of SNe Ic. In our scenario the conversion energy is emitted after the SN shock breakout, mostly in neutrinos. However, if quark stars are formed then they are essential as a source of an ultrarelativistic outflow. A quark star surface acts as a membrane confining quarks to the stellar volume, which constitutes a huge bubble (bag) of the quantum chromodynamics vacuum. The membrane allows for absorption of baryons by SQM, where they dissolve into quarks. At the temperatures under consideration, this membrane may be crossed only by electrons and positrons, photons, neutrino pairs and magnetic fields, automatically generating the conditions needed for an ultrarelativistic outflow of classical GRBs.

The concept of an outflow from a compact star collimated into a narrow jet has been around for decades (LeBlanc & Wilson 1970; Mori et al. 2004). This is not to claim that the problem has been theoretically solved, but the relativistic outflow from a hypothetical quark star does not create any new problems. In fact, the relativistic outflow should be made easier with the generation of baryon-free ejection.

We do not propose to solve the collimation problem, as this is common to all GRB models, and the presence of jets is supported by numerous observations (cf. Stanek et al. 1999, and reference therein). We do not propose a novel solution for an SN explosion; we know that SNe explode. The issue that we propose to solve with quark stars is the generation of ultrarelativistic outflows.

We consider the formation of a hot quark star at the SN Ic centre. The pre-SN Fe–Ni core collapses into a proto-neutron star. The structure and evolution of a proto-neutron star have been recently studied by Pons et al. (1999, 2001a,b), and its dynamics by Villain et al. (2004) and Ferrari, Miniutti & Pons (2003). Neutrinos trapped in dense matter enforce its high electron fraction (∼30 per cent), stiffen the equation of state, and prohibit the formation of hyperons. All these effects result in a relatively low central density ($\sim 5 \times 10^{14}$ g cm^{-3}), and a large radius of the proto-neutron star (∼50 km). However, within a minute or so an excess of electron neutrinos diffuses out, and the electron fraction in the core falls to the usual ∼10 per cent. This deleptonization allows for the appearance of hyperons, which additionally softens the equation of state. The central density rises to $\sim 10^{15}$ g cm^{-3}, and the temperature rises to some 5×10^{11} K: a hot neutron star is born.

Just after the formation of a hot dense neutron star the conditions at the neutron star centre (density $\sim 10^{15}$ g cm $^{-3}$ and temperature $\sim 5 \times 10^{11}$ K, with a significant fraction of hyperons) allow for the nucleation of a quark matter nugget which then absorbs the whole neutron star within minutes (Olinto 1987; Heiselberg & Pethick 1993): a quark star is born. Conversion of baryonic matter into SQM is strongly exothermic, releasing some ∼50 MeV or more per absorbed baryon. Most of that energy is lost in neutrino–antineutrino emission within fraction of a minute, just as happens with the initial gravitational collapse when the hot neutron star forms. Conversion of the outer layers of a neutron star into SQM is facilitated by strong evaporation of nuclei into a neutron gas due to the very high temperature. The newborn quark star is a huge reservoir of energy, including thermal energy of quarks, which for simplicity are assumed to be normal (non-superconducting) at the prevailing temperatures. Quarks move freely within a huge bag constituting the quark star but they cannot cross the confining bag surface. However, electrons and positrons, neutrinos, photons and the magnetic field are not subject to strong interaction; they can leave the quark bag which plays the role of a membrane filtering pure energy from hot quark matter. This outflow of energy carrying zero baryon number can be a genuine progenitor of a GRB associated with an SN Ic.

The duration of the pure energy outflow from the hot, rotating quark star is uncertain, and can be seconds or many minutes, depending on the relative importance of differential rotation and magnetic fields in the quark star energy sharing. The details of the evolution of a differentially rotating quark star are beyond the scope of this paper.

The initial spectrum of the GRB near the quark surface is very specific (Usov 1998, 2001; Page & Usov 2002). However, the enormous optical depth modifies this original spectrum beyond recognition. We cannot provide any spectral information that could be used as a direct diagnostic of quark star formation.

4 DISCUSSION AND CONCLUSIONS

Our suggestion that GRBs are related to the formation of quark stars is mostly driven by the perceived difficulty in generating bulk Lorentz factors as large as 300, while at the same time keeping the energy density, and therefore the optical depth, very large. Notice that the criticism of the neutron star–quark star conversion model of GRBs by Fryer & Woosley (1998) does not apply to our scenario. In other words, in our case the phase transition occurs on a time-scale much longer then the dynamic one, and therefore does not provoke an outgoing shock, which would load the energy outflow too much with non-relativistic matter.

We cannot provide a proof that quark stars exist, but we have a hint: the apparent bimodality of SN Ic properties. Some generate soft and weak bursts, like GRB 980425/SN 1998bw, with no evidence for ultrarelativistic jets. Some generate strong GRBs with ultrarelativistic jets, like GRB 030329/SN 2003dh. With the pointing accuracy of *Swift*, SNe like 1998bw will be readily detected, following the breakout of a shock at the stellar surface. The time to the breakout is estimated to be approximately half a minute after the core collapse (Woosley, private communication; Deng, private communication). If the SN generates a relativistic jet in our direction, the soft precursor caused by the breakout will be followed by a regular GRB a minute or several minutes later, depending on the poorly known details of the transition from a neutron star to a quark star (Olinto 1987; Heiselberg & Pethick 1993). *Swift* should improve the statistics of SNe Ic, and the existence of precursors, and the issue of whether there is a bimodal distribution of SNe Ic will be observationally resolved.

Recent analysis of BATSE data by Lazzati (2005) indicates that the precursors have already been detected, and if our interpretation is correct they offer evidence for the formation of quark stars following a SN Ic explosion. The time interval between the onset of a precursor and the beginning of the main GRB, $t_1 - t_2$, can be used as a diagnostic for the transition from a hot neutron star to a hot quark star.

Needless to say, if the bimodality is confirmed, we will be strongly motivated to develop details of our model, including the effects of quark superconductivity, and to use the quantitative description of stellar rotation, formation and dissipation of magnetic field, as well as to describe the energy transport in a more detailed way.

While we consider the quark star solution to the problem of SN Ic bimodality, we realize that this may be a result of rotation, with high core angular velocity being responsible for the relativistic jets. The best argument that we may offer in favour of quark stars at this time is the time lags discovered by Lazzati (2005), provided that the reality of precursors is confirmed.

The duration of GRB activity, observed to be up to several minutes or more, may well be due to a gradual dissipation of differential rotation by the magnetic fields. The infall of fresh nuclear matter following the initial core collapse may provide not only an input of angular momentum but also a supply of fresh baryons which will increase the mass of the quark star. Ultimately, the quark star may collapse into a black hole, terminating the GRB activity.

Swift may provide information about the time lag between the beginning of strong GRB activity and the arrival of a shock at the surface (the breakout, or a precursor). With the present state of the theory it is not even possible to predict which may come first. It will certainly be important to find out observationally what is the relation between the ultrarelativistic jet and the breakout of a more or less spherical component of an SN Ic explosion. Can the two components be identified? What is the time interval between them?

The distribution of long-lag GRBs found by Norris (2002) indicates that these may be associated with SNe like 1998bw, and *Swift* will be able to provide a definite answer to the question: are these GRBs beamed away from us, or are they approximately spherical explosions as envisioned by Colgate (1968)?

It is somewhat disturbing that, out of several dozen GRBs detected with *Swift*, and half a dozen redshift determinations (all with $z > 1$), not a single SN was detected. Given the dominance of long-lag GRBs at the faint end of BATSE (Norris 2002), and their 'Euclidean' counts, some of those were expected to be relatively nearby, and hence to produce easily detectable SNe Ic.

While we cannot be quantitative in our description of GRB energetics and spectra, it appears to us that quark star-driven bursts are electromagnetic, rather than gas dynamical; the electromagnetic origin of GRBs was proposed by Blandford (2002) and Lyutikov & Blandford (2004).

A problem with a standard GRB model, be it of a fireball or an electromagnetic type, is the need to separate baryons from energy. This includes Kluźniak–Ruderman (Kluźniak & Ruderman 1998) and Usov (1992) models. Note that the strong magnetic fields are generated with a dynamo process. This can bring the field up to equipartition with the kinetic energy of moving baryons, and makes the effective Lorentz factor only slightly larger than 1. It takes time to separate the field from the baryons. It is clear that on a long enough time-scale such a separation happens, as demonstrated by magnetospheres of radio pulsars. It is not obvious that the separation of magnetic energy from baryons can be done on a time-scale of seconds, and proceed up to Lorentz factor $\Gamma \sim 300$. In our scenario we begin with a baryon-free ultrarelativistic flow from a quark star, and we have to avoid mixing it with contaminating baryons. Photons, electron–positron pairs and magnetic fields are difficult to mix with baryons, and are likely to remain separated. In any case it is easier to maintain a relativistic flow then to separate this flow from baryons.

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REFERENCES

Alcock C., Farhi E., Olinto A. V., 1986, ApJ 310, 261
Berezhiani Z., Bombaci I., Drago A., Frontera F., Lavagno A., 2003, ApJ, 586, 1250
Berger E., Kulkarni S. R., Frail D. A., 2004, ApJ, 612, 966
Bietenholtz M. F., Bartel N., 2005, ApJ, 625, L99
Blandford R. D., 2002, in Gilfanov M., Sunyaev R., eds, Lighthouses of the Universe. Springer, Berlin, p. 381
Bombaci I., Datta B., 2000, ApJ, 530, L69
Cheng K. S., Dai Z. G., 1996, Phys. Rev. Lett., 77, 1210
Chevalier R. A., Li Z.-Y., 1999, ApJ, 520, L29
Clark J. S., Goodwin S. P., Crowther P. A., Kaper L., Fairbairn M., Langer N., Brocksopp C., 2002, A&A, 392, 909
Colgate S. A., 1968, Canad. J. Phys., 46, 476
Dai Z. G., Lu T., 1998, Phys. Rev. Lett., 81, 4301
Della Valle M., 2005, in Piro L., Amati L., Covino S., Gendre B., eds, 4th Workshop Gamma-Ray Bursts in the Afterglow Era. II Nuovo Cimento, in press (astro-ph/0504517)
Deng J., Tominaga N., Mazzali P. A., Maeda K., Nomoto K., 2005, ApJ, 624, 898
Drago A., Lavagno A., Pagliara G., 2004, Phys. Rev. D, 69, 057505
Ferrari V., Miniutti G., Pons J. A., 2003, MNRAS, 342, 629
Figer D. F., Najarro F., Geballe T. R., Blum R. D., Kudritzki R. P., 2005, ApJ, 622, L49
Filippenko A. V., 1997, ARA&A, 35, 309
Frail D. A., Waxman E., Kulkarni S. R., 2000, ApJ, 537, 191
Fryer C. L., Woosley S. E., 1998, ApJ, 501, 780
Gaensler B. M., McClure-Griffiths N. M., Oey M. S., Havekorn M., Dickey J. M., Green A. J., 2005, ApJ, 620, L95
Galama T. J. et al., 1998, Nat, 395, 670
Gehrels N. et al., 2004, ApJ, 611, 1005
Granot J., Loeb A., 2003, ApJ, 593, L81
Haensel P., Zdunik J. L., Schaeffer R., 1986, A&A, 160, 121
Haensel P., Paczyński B., Amsterdamski P., 1991, ApJ, 375, 209
Heger A. et al., 2003, ApJ, 591, 228
Heiselberg H., Pethick C. J., 1993, Phys. Rev. D, 48, 2916
Iwamoto T. et al., 1998, Nat, 395, 672
Kaper L., Lamers H. J. G. L. M., Rymaekers E., van den Heuvel E. P. J., Zuidervijk E. J., 1995, A&A, 300, 446
Klebesadel R. W., Strong I. B., Olson R. A., 1973, ApJ, 182, L85
Kluźniak W., Ruderman M., 1998, ApJ, 508, L113
Lazzati D., 2005, MNRAS, 357, 722
LeBlanc J. M., Wilson J. R., 1970, ApJ, 161, 541
Lee H. K., Wijers R. A. M. J., Brown G. E., 2000, Phys. Rep., 325, 83
Lyutikov M., Blandford R., 2004, astro-ph/0312347
Malesani D. et al., 2004, ApJ, 609, L5
Meszaros P., Rees M. J., Wijers R. A. M. J., 1998, ApJ, 499, 301
Mori K., Burrows D. N., Hester J. J., Pavlov G. G., Shibata S., Tsunemi H., 2004, ApJ, 609, 186
Norris J. P., 2002, ApJ, 579, 386
Olinto A. V., 1987, Phys. Lett., B192, 71
Ouyed R., Sannino F., 2002, A&A, 387, 725
Paczyński B., 1998, ApJ, 494, L45
Paczyński B., 2001, Acta Astron., 51, 1
Page D., Usov V. V., 2002, Phys. Rev. Lett., 89, 131101
Pons J. A., Reddy S., Prakash M., Lattimer J. M., Miralles J. A., 1999, ApJ, 513, 780
Pons J. A., Steiner A. W., Prakash M., Lattimer J. M., 2001a, Phys. Rev. Lett., 86, 5223
Pons J. A., Miralles J. A., Prakash M., Lattimer J. M., 2001b, ApJ, 553, 382
Soderberg A. M., Frail D. A., Wieringa M. H., 2004, ApJ, 607, L13
Stanek K. Z., 2004, astro-ph/0411361
Stanek K. Z., Garnavich P. M., Kaluzny J., Pych W., Thompson I., 1999, ApJ, 522, L39
Stanek K. Z. et al., 2003, ApJ, 591, L17
Stanek K. Z. et al., 2005, astro-ph/0502319
Stockdale C. J., Van Dyk S. D., Sramek R. A., Weiler K. W., Panagia N., Rupen M. P., Paczyński B., 2004, IAUC 8282
Stockdale C. J. et al., 2005, IAU Circ. 8472
Tan J. C., Matzner C. D., McKee C. F., 2001, ApJ, 551, 946
Taylor G. B., Frail D. A., Berger E., Kulkarni S. R., 2004, ApJ, 609, L1
Usov V. V., 1992, Nat, 357, 472
Usov V. V., 1998, Phys. Rev. Lett., 80, 230
Usov V. V., 2001, ApJ, 550, L179
Vanderspek R. et al. (HETE), 2004, ApJ, 617, 1251
Villain L., Pons J. A., Cérda-Durán P., Gourgoulhon E., 2004, A&A, 418, 283
Wang X. Y., Dai Z. G., Lu T., Wei D. M., Huang Y. F., 2000, A&A, 357, 543
Waxman E., 2004, ApJ, 602, 886
Witten E., 1984, Phys. Rev. D, 30, 272
Woosley S. E., 1993, ApJ, 405, 273
Zeh A., Klose S., Hartmann D. H., 2005, astro-ph/0503311

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